Renewable and Sustainable Energy Reviews 56 (2016) 1272–1292

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on modeling and simulation of building energy systems

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A R T I C L E I N F O

Article history:
Received 22 January 2015
Received in revised form
30 November 2015
Accepted 3 December 2015
Available online

Keywords:
Building energy systems
Occupancy
Energy model
Comfort
Building energy simulation

A B S T R A C T

Buildings consume about 40% of the overall energy consumption, worldwide and correspondingly are also responsible for carbon emissions. Since, last decade efforts have been made to reduce this share of CO_2 emissions by energy conservation and efficient measures. Scientist across the world is working on energy modeling and control in order to develop strategies that would result in an overall reduction of a building's energy consumption. Development of control strategies asks for a computationally efficient energy model of a building under study. This paper presents a review of all the significant modeling methodologies which have been developed and adopted to model the energy systems of buildings. Attention is majorly focused on the works which involved development of the control strategies by modeling the building energy systems. Models reviewed are presented categorically as per the modeling approach adopted by the researchers. Simulation programs and softwares available for building energy modeling are also presented.

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http://dx.doi.org/10.1016/j.rser.2015.12.040
1364-0321/

1. Introduction

A number of methods have been developed to construct load models or energy consumption models that simulate a building/plant system for load prediction or cost saving estimates. Such models vary in magnitude from modeling of a single slab (or a wall) [1] to modeling of a complete building through modeling of rooms subjected to temperature variations. Clarke [2] gave a three stage process for model formulation. In the first step, the building system is converted from continuous state to a discrete state. This involves selection of nodes at the points under study, representing the homogeneous or non-homogeneous control volumes like that of internal air mass, boundary surfaces, building fabric elements, Renewable Energy Systems, equipment of the room, etc. Equations satisfying mass, momentum and energy conservation principles are developed in the second step for each node which is in thermodynamic contact with its surrounding nodes. Last step involves solving the equations derived in the second step for successive time steps to obtain state variables of the node for future time periods as a function of present time state variables with the boundary conditions prevailing at both times.

1.1. Energy consumption in buildings

Driven by the rising population, expanding economy and a quest for improved quality of life, energy consumption has increased and the growth rates are expected to continue, fuelling the energy demand further. Increased energy consumption will lead to more greenhouse gas (GHG) emissions with serious impacts on the global environment. The expected increase in energy demand, along with the predominance of coal in the energy mix, highlights the significance of promoting energy efficiency. Higher rate of urbanization with increased floor space for both residential and commercial purposes has imposed enormous pressure on the existing sources of energy. Limited availability of energy the existing energy resources and highly transient nature of renewable energy sources have enhanced the significance of energy efficiency and conservation in various sectors.

Consumption of electricity has increased in the commercial sector in the past ten years. In commercial buildings, the annual energy consumption per square meter of the floor area is in excess of 200 kW h with air-conditioning and lighting serving as the two most energy consuming end-use applications within a building. Growth in buildings sector energy consumption is fueled primarily by the growth in population, households, and commercial floor space, which are expected to increase by 28% within 2035.

In order to account for the thermo-visual comfort of the occupants and according to functionality (manufacturing, etc), the HVAC systems, lighting systems, electric motors are the major consumers of energy within the buildings sector. Categorical classification of energy consumption by any end use such as heating, cooling, cooking, etc. for both residential and commercial buildings (in U.S.) is shown in Fig. 1 [3].

The top four end uses space heating, space cooling, water heating, and lighting—accounted for close to 70% of site energy consumption. Other end uses, such as consumer electronics, kitchen appliances, and ventilation, made up the remainder.

Energy efficiency and conservation measures are predominantly being considered for salvation of the energy requirements in developing nations such as India. Almost 50% of the energy fuel requirements of India are met through foreign imports. This situation of deficit has led to frequent power cuts (load shedding) in major parts of the country, especially during the peak time of the day. [4]. Conservation can, therefore, go a long way in alleviating the resources crunch in the energy supply sector ensuring a more productive use of existing resources.

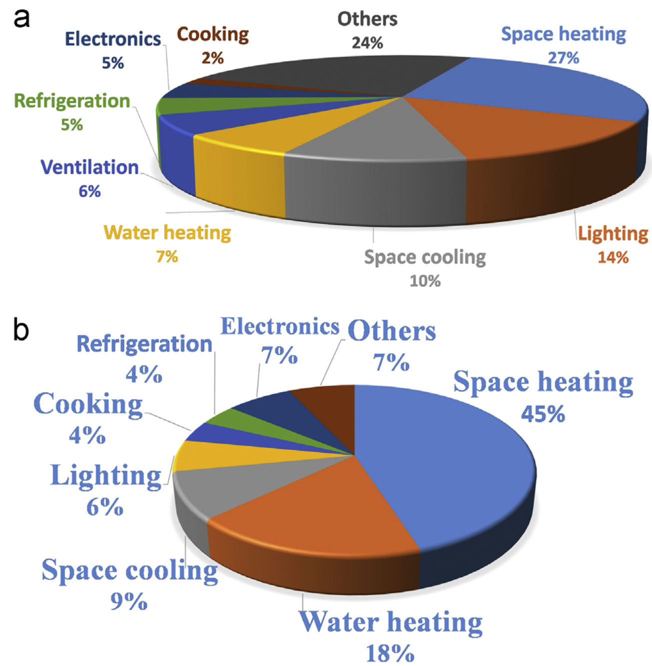

Fig. 1. End use wise energy consumption in (a) residential and (b) commercial, buildings [3].

Energy conservation, which leads to more efficient use of energy without reducing comfort levels, does not mean rationing or curtailment or load shedding, but it is a means of identifying areas of wasteful use of energy and taking action to reduce energy waste. There are vast opportunities to reduce electricity consumption and increase energy efficiency within buildings. It is estimated that new buildings can reduce energy consumption on an average between 20% and 50% by incorporating appropriate design interventions in the building envelope, heating, ventilation and air-conditioning (HVAC, 20–60%), lighting (20–50%), water heating (20–70%), refrigeration (20–70%) and electronics and other (e.g., office equipment and intelligent controls, 10–20%).

1.2. Sustainability

Sustainability is today a goal that just about every organization, institution, business, or individual claims to be striving for, and sometimes claims to have achieved. Given the profound impact of buildings on the environment, the work of HVAC&R design engineers is inextricably linked to sustainability. The engineering sector has seminal influence on building performance, and HVAC&R designers' work is inherently related to overall sustainability in buildings. Sustainability is defined in the ASHRAE GreenGuide [5], in general terms, as "providing for the needs of the present without detracting from the ability to fulfill the needs of the future," a definition very similar to that developed in 1987 by the United Nations' Brundtland Commission (UN 1987). Others have defined sustainability as "the concept of maximizing the effectiveness of resource use while minimizing the impact of that use on the environment" [6] and an environment in which "… an equilibrium … exists between human society and stable ecosystems" [7]. Sustaining (i.e., keeping up or prolonging) those elements on which humankind's existence and that of the planet depend, such as energy, the environment, and health, are worthy goals [5].

This review article is primarily targeted for researchers and scientists engaged in development of control strategies to reduce the energy consumption of a building under study. Most significant part in design of control strategies for building energy control and optimisation is modelling [8]. In almost all control projects, it is crucial to have good precise models of the building energy systems in order to design and tune the controllers and to simulate their performance. A state-of-art review of the significant modeling methodologies developed and adopted to model the energy systems of buildings by researchers round the globe has been presented in this article. There exists a large number of parameter, broadly categorized under *enclosure factors* of thermal properties of materials of construction; *climatic factors* of temperature, humidity and occupancy factors, which influence and act upon the building energy systems. A compact list of all the building energy systems modeling parameters along with their significance and role on the model has been presented. The contents of the paper shall be of prime interests and of benefit to researchers engaged in modeling, simulation and control of building energy systems.

The remainder of the paper is organized as follows. Section 2 introduces the concept of building energy systems (BES), describing mathematical principles of the energy transfer processes occurring within the BES. Section 3 presents modeling approaches adopted by the researchers developing BES model. Section 4 presents detailed literature review of the articles studied and also gives a brief outline of various energy efficiency (EE) and conservation (EC) measures incorporated with BES models. A comprehensive list of parameters involved in BES modeling and simulation is also presented. There are commercially available a few open source building energy simulation software available in the market. A table wise brief of all the BESPs are presented in Section 5. Inferences of the review and study are presented in Section 6.

2. Building energy systems

Building energy systems (BES) can be defined as those which are responsible for consumption of energy in buildings [9]. These can be any physical equipment or machinery or can be a process or a combination of them.

2.1. Building space

In order to maintain thermal comfort, a certain amount of energy needs to be added or removed (heating/cooling) to or from the building space. This energy is majorly dependent on outdoor weather conditions such as outside air temperature, relative humidity and also wind characteristics and also on indoor conditions of occupancy, heat and moisture flow through the walls and interiors, etc. Such energy acts as load on the heating, ventilation and air-conditioning (HVAC) system (for heat and moisture) installed to condition the building space and thus, is called as Building Space Load (BSL). Mathematically, space load is nothing but the rate (heat gain rate) at which energy is being added (heating) or removed (cooling) to or from the building space in order to maintain the space temperature at the desired levels.

Primary objective of HVAC system is to maintain the temperature and moisture content of the building space according to the desired threshold values, devoting due considerations to air motion and quality and noise. Cooling and heating load calculations are the primary design basis for most HVAC systems and components. The reason behind carrying out cooling and heating load calculations is to ensure that the designed HVAC system serves the intended purpose of maintaining the required comfort conditions within the building space.

Accurately performed load calculations for a building space is essential, as such an exercise significantly affects not only the initial costs of design and construction of a building but also the operating costs and hence, the net energy consumption. Load calculations also affect the comfort of the occupants and hence, their productivity. Standard methods [5] are available in the literature to perform load calculations efficiently and reliably and these methods must be used for sizing of building HVAC systems.

Mathematically, the net energy required as input to the building space to maintain the space air temperature at desired comfort levels can be written as:

$$Q_{BSL} = Q_{Loss} - Q_{Gain} \tag{1}$$

where

Q_{BSL}=Building space load, W
Q_{Loss}=Total rate of heat loss, W
Q_{Gain}=Summation of all the heat gains responsible for heating the building space except the HVAC system, W

Now, for carrying out load calculations it is essential to have knowledge of various energy transfers that take place across the conditioned space, which will influence the required capacity of the air conditioning equipment. Cooling and heating load calculations involve a systematic step-wise procedure by following which one can estimate the various individual energy flows and finally the total energy flow across an air conditioned building.

In order to understand the various energy transfer processes taking place within a building space, let us consider a fictive perimeter room of a building as shown in fig. The room is built of multilayered walls all around, one of which is equipped with a window physically separating the room from the outside environment. Adjacent wall separates the room from adjoining rooms and a floor and a ceiling wall up and below. The room space is conditioned by a HVAC system, of which an Air Handling unit (AHU) is depicted in Fig. 2. The room has normal lighting and other electronic equipment which can also dissipate and absorb heat.

All the three modes of heat transfer processes viz., conduction, convection and radiation take place within the room space. Sensible heat transfer takes place within the conditioned room space through conduction, convection, and/or radiation whereas Latent heat transfer occurs due to transfer of moisture (emission of water vapour by in room equipment and occupants) in and out of the room space. The building elements of the room which are responsible for heat and mass transfer processes are given in Table 1.

Now, the heat loss rate of Eq. (1) can be given as:

$$Q_{Loss} = Q_{Component} - Q_{Ventilation} \tag{2}$$

where

$Q_{Component}$=Heat loss rate due to a building component or element within a building envelope or enclosure such as a wall, roof, etc., W
$Q_{Ventilation}$=Heat loss rate due to ventilation by the HVAC system, W
$Q_{Component}$ and $Q_{Ventilation}$ are then calculated, generally for steady state conditions, using the *U*-values of the elements and the mass flow rates, respectively.

The HVAC systems majorly responsible for the occupants comfort humidify or de-humidify the room space as per the outside climatic conditions. For example, in extremely dry climates, humidification may be required, rather than dehumidification, to maintain thermal comfort. Depending upon the application, HVAC systems conditioning a building space are sized with over estimation for commercial and a few industrial applications and under sized for some other industrial and for residential buildings. Peak

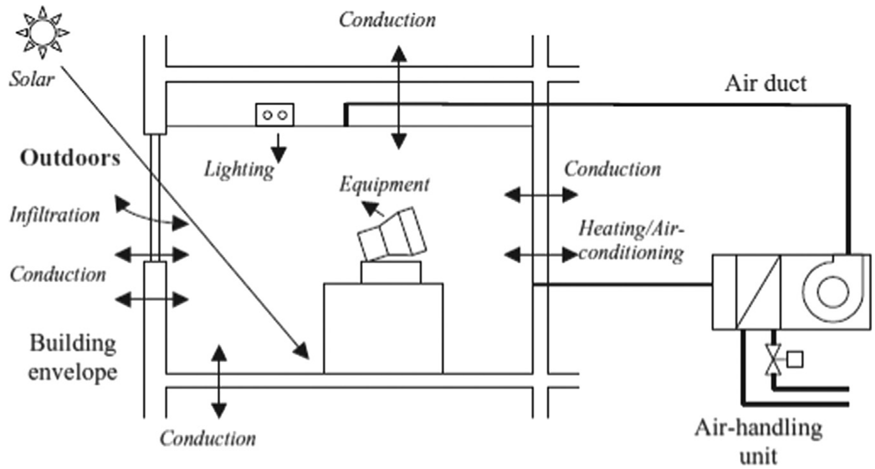

Fig. 2. Energy transfer processes taking place within a building space conditioned by a HVAC plant [10].

Table 1
Building elements and modes of heat and mass transfer processes.

Heat and mass transfer processes	Building elements
Conduction and/or radiation heat transfer	External wall, roof, ceiling and floor slabs and internal partition wall, doors, skylights.
Conduction heat transfer and solar radiation transmission.	Window glazing
Conduction and/or radiation heat transfer and moisture dissipation	Occupants, lights, and other equipment
Convection heat and mass transfer	Infiltration from outside and adjoin rooms/lobby

design heating and cooling load calculations seek to determine the maximum rate of heating and cooling energy transfer needed at any point in time. Similar principles, but with different assumptions, data, and application, can be used to estimate building energy consumption.

2.2. HVAC systems

Heating, Ventilation and air conditioning (HVAC) systems have a large impact on the net energy consumption of buildings. Not only do they consume about 40–60% of the total electricity of commercial buildings but they also have a large influence on the occupant's comfort and behavior and thus, on building profitability. Since last decade HVAC systems have received attention during planning and designing for attaining energy conservation in buildings. However, it remains a challenge for building personnel for handling of HVAC systems to optimize energy consumption without compromising thermal comfort within the building premises.

Within HVAC systems, compressors consume maximum amount of energy followed by chiller water pumps and condenser water pumps which account for 11% and 7%, respectively. The Air-Handling Units (AHUs) and cooling towers consume 13% and 3% respectively of the total HVAC system input electrical energy [11]. Remaining amount of energy is consumed within fan coil units (as is evident from Fig. 3).

Also, the components of a particular HVAC system are selected and designed as per already carried out load calculations for a building space to be conditioned. The size of piping, boilers, diffusers, ductwork, chillers, coils, compressors, air handlers, fans, and any other component of a HVAC system are selected according to the load calculations.

2.3. Lighting systems

Lighting systems account as a significant component of energy costs for commercial buildings. For instance, lighting systems account for about 30% of the electricity consumed in a particular fully conditioned office building and more than 30% for a non-air-conditioned office. Hospitals consume about 20–30% of the electricity for lighting. Connected load in commercial building varies from 15–25 W/m^2.

Now, lighting systems not only account for a particular share of the building's energy consumption but also act as space load as they dissipate appreciable heat during their operation. Needless to mention, such a heat dissipation can serve as heating source and thus, come to rescue for cold climatic condition buildings. IES [12] recommends illuminance levels for visual tasks and surrounding lighted areas. The energy consumed by a lighting installation depends upon the power consumption of the luminaries and the amount of time for which they are switched on. Both of these aspects are important, as changes in either will affect the energy efficiency of the installation. Information about the consumption of energy of an existing or proposed lighting installation when considering the cost-effectiveness of measures to improve its energy efficiency.

Energy consumed by a lighting system is given as:

$$E_T = P_L \times T_U \tag{3}$$

where

E_T=Total energy consumed by the lighting system
T_U=Usage time which is the amount of type for which the particular lighting installation has been under use or consuming energy.
P_L=Installed lighting load of the building which is given by:

$$P_L = n \times P_{lum} \tag{4}$$

where

n=number of each type of luminaries
P_{lum}=Power capacity of the luminaries, manufacturing data

Now, usage of a lighting installation depends upon the occupancy patterns of the space, the daylight available in the space and the control system used. Also, for lighting installation that can be dimmed, it is not possible to derive energy consumption simply from total installed load and hours of use, since the energy consumption at any time will depend on the actual level of output of the lamps at that time.

2.4. Occupancy and comfort

Good indoor air quality is necessary for maintaining health and high productivity. Consequently, green and sustainable building rating systems, such as the U.S. Green Building Council's (USGBC), Leadership in Energy and Environmental Design (LEED®) program, place great importance on creating and maintaining acceptable IAQ.

3. BES model development and approach

Energy requirements of the building energy systems such as building space, HVAC systems, lighting systems etc. directly affect building's operating cost and indirectly affect the environment. This section discusses methods for estimating energy use for two purposes: modeling for building and HVAC system design and associated design optimization (forward modeling), and modeling energy use of existing buildings for establishing baselines, calculating retrofit savings, and implementing model predictive control (data-driven modeling) [13–16].

3.1. Model development

Models developed to simulate the building energy systems can be divided into many types. Basically, models are classified as physical, symbolic and mental models. Symbolic models are comparatively less complex and are thus frequently used. Models can be mathematical and non-mathematical models. Development of mathematical model of a system involves mapping of the physical laws governing the dynamics of the system's process into mathematical relations using variables and constants. Due to ease in evaluation and manipulation mathematical models are the most suitable and the most widely used category of models [17]. Mathematical models can be of theoretical and experimental type. As name suggest, theoretical models involve breaking down of a larger system under study into a number of smaller and simpler subsystems. Mathematical equations constrained through physical laws are then used to relate the different subsystems. On the other hand, experimental models are developed through empirical relations i.e., through measurement of input and output signals of the system and then, evaluating the system's response. Such models do not provide any information about the mechanics or behavior of the system. Differential or difference equations along with the use of soft computing techniques like fuzzy are made use of in experimental modeling.

In general, an energy system model is a mathematical model describing the behavior of the system. Modeling structure for any energy system is made up of three building blocks viz., input variables, output variables and the system itself [18], as shown in Fig. 4.

The process of modeling the energy system involves determining any one of the three building blocks when adequate information about the other two blocks are available. This is what classifies the energy models as White-box, Black-box or grey-box models. Such a classification of the models is described in detail in the following sections of the paper.

As is clear from Fig. 4, the input variables, also called as regressor or forcing variables, is the building block of the modeling system that acts on the building energy system. Variables such as internal (causal) heat gains, thermostat set point settings, etc which can be controlled by the system engineer are regarded as controllable input variables. On the other hand, solar radiation, outdoor air temperature and wind speed, etc are some of the input variables whose characteristics can't be controlled but at the maximum can only be forecasted by using suitable techniques. For a building energy system model, room air space temperature and humidity are the output variables. Such variables describe the reaction of the building energy system to the input variables. In certain cases, the net energy consumption or energy use is also the output for a BES model. BES modeling structure describes the

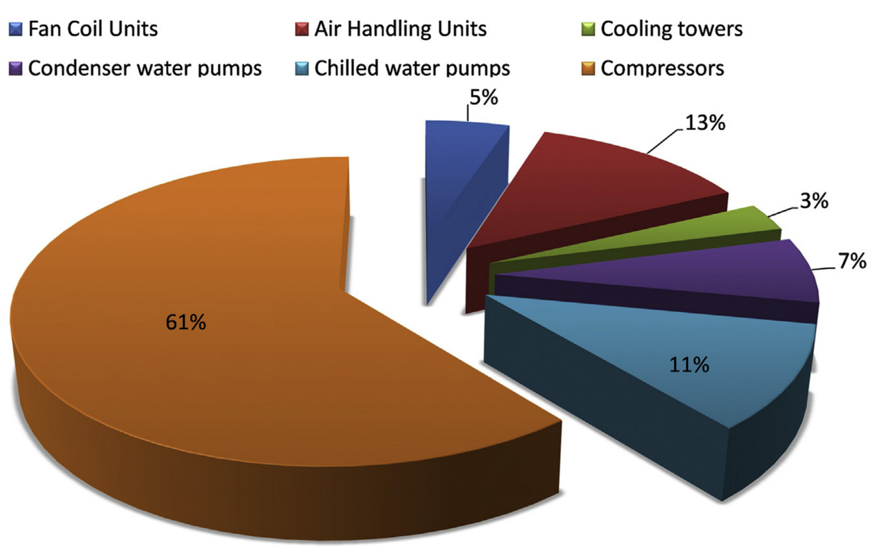

Fig. 3. Sub-system wise energy consumption for a particular HVAC system.

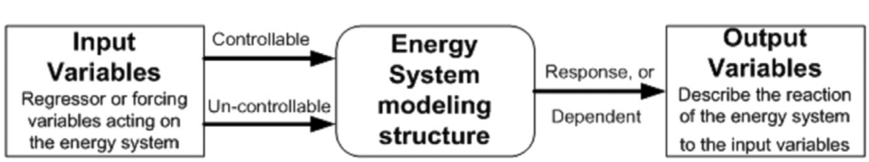

Fig. 4. Modeling structure of a BES.

complete BES providing all the necessary hygro-thermal description of the systems. Mathematical equations of all the energy transfer processes are used to build the structure of the BES system.

3.2. Modeling approach

According to Rabl [19], there are two broad and distinct approaches to BES modeling and as per the prime objective of the modeling process one of the approaches is followed [20]. Such approaches are broadly classified as:

3.2.1. Forward approach

Development of a BES model using forward approach involves prediction of the output variables using detailed structure and parameters of the model subjected to a specific set of input variables. Models developed practicing such an approach are called as White-Box models. Such models are highly accurate as most of the energy transfer processes are mapped into development of the BES modeling structure. Also, with increased trends of sophistication in computing techniques BES models with high accuracy have been possible now-a-days. This bears an advantage as the BES is not required to be constructively built, thereby saving time and money. Forward modeling of BES is practiced in the stages of preliminary design and analysis during the detailed energy audit process.

Step-wise procedure for forward approach modeling is given below. It is to be noted that the procedure is not universal but instead, has been followed by most of the development engineers whose works have been reviewed in this paper.

Step 1: Acquire Climate data as per location of the building under study.

Step 2: Acquire building design data.

Step 2.1: Acquire building geographical characteristics: location, orientation, etc.

Step 2.2: Acquire building construction data: Thermo-physical properties of the building materials, etc.

Step 3: Heat plant characteristics

Step 3.1: Type of HVAC system

Step 3.2: Type and characteristics of the HVAC subsystems: AHU, Coil units, etc.

Step 4: Building operating schedules

Step 5: Simulate the model as per the desired simulation periods

Step 6: Predict the net energy (peak or average values) consumption patterns.

Such a procedure is beneficial to the under graduate and graduate scholars working on the modeling of BES. BES simulation softwares of TRNSYS, DOE-2, EnergyPlus, and ESP-r work on the same procedure.

3.2.2. Data driven approach

As the name suggests, such an approach involves development of BES model driven by the knowledge of the input and the output data. Such data is available through measurements acquired through experimental procedures or are already known. In cases where BESs are already been built, such an approach is made use of utilizing the performance data available through experiments being carried out within the building space. Such data is categorized as: Intrusive and non-intrusive data. Table 2 illustrates the types of data acquired for development of a BES model.

Also called as Black-box models, in this approach, BES model structure is estimated using single variable or multi-variable regression analysis carried out between measured output variables of net energy consumption and the various other parameters of occupancy, solar and wind data. The form of the regression models can be either purely statistical or loosely based on some basic engineering formulation of energy use in the building. In case of long term simulations (monthly or quarterly and more), it is time consuming and a costly affair to record the variables all along the simulation periods. In such cases, the parameters of the model are estimated using artificial learning techniques such as Artificial Neural networks (ANN), Fourier series, etc. In such a situation, the identified BES model parameters bear very little/negligible physical significance.

With the advent of artificial learning or searching techniques, the performance data to be measured is less. This saves a lot of time and computing memory. Moreover, in commercial or office buildings, daily operations as per occupancy schedules and set point temperature values are often repetitive. Thus, the data-driven model contains a relatively smaller number of parameters to be measured because of the limited repetitive information contained in the performance data. This makes a data driven black box model fairly simpler but less accurate than the forward or white box models.

However, as the BES model parameters are estimated on the basis of actual performance data within the building space, data driven models are fairly accurate with regard to the computational intelligence and power. But this also, makes the measurement of data and data readings a highly significant process. Skillful engineers are required to practice such an exercise in order to acquire tailor made procedure for data collection and measurement.

Both forward and data driven approaches are also used for modeling subsystems of a HVAC system [21–27]. Data driven approach also assists in on line controlling and diagnosis of the HVAC system. BES modeling approaches also govern evaluation of Demand Side Management (DSM) schemes implemented to a specific building [16,28–55].

3.2.3. Grey box approach

This approach first formulates a physical model to represent the structure or physical configuration of the building or HVAC&R equipment or system, and then identifies important parameters representative of certain key and aggregated physical parameters and characteristics by statistical analysis [20]. This requires a high level of user expertise both in setting up the appropriate modeling equations and in estimating these parameters. Often an intrusive experimental protocol is necessary for proper parameter estimation. This approach has great potential, especially for fault detection and diagnosis (FDD) and online control, but its applicability to whole-building energy use is limited. Examples of parameter estimation studies applied to building energy use are [19,21,33,34,56,57–64].

4. Literature review

Through energy efficiency measures for buildings, the energy consumption in a building can be reduced while maintaining or improving the level of comfort in the building. Operational and design measures to practise energy efficiency in buildings have been reviewed. Such measures can typically be categorized into (Table 3):

Several literary articles, starting from early 90s and late 80s till date have been reviewed. The literature contains descriptions of relevant dynamic models developed for buildings. Models developed both for building construction elements and HVAC plants have been reviewed. Summary of all the works have been presented in Table 4 and a detail review is presented.

Gouda et al. [96] developed a method for tuning the parameters of a reduced-order lumped parameter model to derive a low-order model. The model involved combining a construction element (external walls, internal partition, door and ceiling) combined to

Table 2
Types of data available for data driven BES model.

Intrusive data	Nonintrusive data
Gathered under conditions of pre-determined or planned experiments on the system to elicit system response under a wider range of system performance than would occur under normal system operation to allow more accurate model identification	When constraints on system operation do not allow such tests to be performed, the model must be identified from nonintrusive data obtained under normal operation.

Table 3
Various energy efficiency (EE) and conservation (EC) measures incorporated with BES models.

EE/EC measures	Work sources
Reducing heating demand	[5,65–69,10]
Reducing cooling demand	[5,65–69,10,70–72,17,73–75]
Reducing the energy requirements for ventilation	[5,65–69,10,70–72,76,77–80,17,81–84]
Reducing energy use for lighting	[5,10,12,65,66]
Reducing electricity consumption of office equipment and appliances	[5,10,16,33,34,36,38,40]
Good housekeeping measures	[5,10]

form two "lumped" thermal resistances and one thermal capacitance, values of which were computed by a mathematical formula. A nonlinear multi-variable constrained optimization problem driven by Kuhn–Tucker equations was formulated and applied to minimize the square root of the sum-squared-error between the step responses of the 20th order model and the 2nd order model by varying its *R* and *C* parameters. Optimizations were carried out on individual construction elements for unit step disturbances in two excitation variable types: the external temperature and internal surface heat transfer.

Fraisse et al. [97] modeled a multi-layer wall using electrical analogy method. Conduction through the walls was represented with a 3R4C model and the conductive exchanges through windows, convective exchanges and LW radiative exchanges were modeled using a 1R model. The water loop of the heating floor was modeled by 2R1C network. 3R2C, 3R4C and 1R2C models were compared with a reference solution obtained by discretizing the wall into 100 nodes, related to spectral analysis, step change in temperature and frequency analysis (bode diagrams). A hydraulic heating floor was integrated to the developed analogical building model in order to limit the problems of convergence during numerical simulations. TRNSYS was used to develop the model.

Hudson and Underwood [98] developed a lumped capacitance model of a room consisting of external wall and internal floor, ceiling and partition walls in MATLAB–SIMULINK. Heat supplied by the plant, internal causal heat gain, solar radiation through glazing and the external air temperature were taken as inputs to the model. As the model was developed for short term dynamics, the initial temperature of the internal structure was set at the room air temperature at the start of the cooling period. Such an assumption however is invalid for rooms with significant solar gains.

Wang and Xu [70–72] developed a method to identify the parameters of a simplified building model based on frequency characteristic analysis. Such an analysis involved identifying the parameters of the model using the thermo-physical properties of the building and short term operation data mnonitored. 3R2C model was used to simulate the building envelope and the optimal nodal placement of the model was obtained by matching the theoretical frequency response characteristics of the building envelope with the frequency response characteristics of the simplified model using GA estimators. The developed methodology involved computing the theoretical frequency characteristic of heat transfer of the building envelope, followed by deducing the frequency characteristic of the simplified model and then developing an objective function of minimizing the amplitude and phase lag of the theoretical and the simplified model. Energy consumption of the simplified model was predicted using differential equations and a Runge Kutta algorithm was used to compare it with the measured cooling load.

McKinley and Alleyne [99] developed a process to determine a building's time invariant parameters and time-varying source terms. The building model consisted of a thermal network representing the building structure, coupled to the air mass or zone inside the building. The outer load is caused by solar irradiation absorbed by exterior walls and roofs. The inner load is due to solar irradiation transmitted through windows and subsequently absorbed on interior walls, floors, and furnishings. EnergyPlus building simulations were used to compute the source terms.

Laret [100] developed a simplified dynamic model of a building zone in which doors and windows categorized as "light external walls" were modeled by a 1R network. Massive external walls i.e., walls with a high mass and high insulation from the outdoor were modeled as a 2R1C network and massive internal walls were modeled with adiabatic boundary conditions by a 1C network to include the mass of the air flowing through the zone under study. Such a network modeled developed by Laret is shown in Fig. 5.

The walls of the building zone under study, surrounding the zone and in contact with the outdoor were categorized as external walls. They include walls in contact with cold neighbor zones, such as outdoor car parks, whose temperature is strongly influenced by the outdoor temperature. Internal walls entirely involved in the zone under study were named as internal walls which included walls and floors entirely included in the zone under study and internal walls dividing the building into different zones were called as partition walls including walls in contact with neighbor zones heated or cooled following a schedule similar to the zone under study. Parameters of the model were deduced through indoor temperature response analysis with step inputs of indoor heat flow and outdoor temperature through Laplace transformations. Boundary conditions for external walls and internal walls (for the Zone side of the wall) were of Fourier type, denoting that the heat exchange is related to the wall environment temperature as well as boundary later convection and radiation heat transfer coefficient. Internal walls for the null heat flow plane wall side had Neumann conditions as the boundary condition.

Ngendakumana [101] further developed the model (Fig. 6) proposed by Laret [100] based on the electrical analogy of thermal networks.

Masy [75] upgraded the model by adding a specific outdoor branch connected to an outdoor equivalent temperature, in order to account for solar heat gains and infrared heat losses through the roof. A series R–C branch was added to account for the mass of internal walls entirely included into the zone under study. Such internals walls were subjected to identical temperature and heat flow signals on both surfaces and thus, there was no transfer of heat across them. The parameters of the walls were tuned using sinusoidal response (Fig. 7) instead of step response.

A zone admittance matrix was computed through the sum of the wall network admittance matrixes multiplied by their corresponding areas to carry out the wall (both external and internal) adjustment process. External walls were modeled with isothermal boundary conditions walls. Whereas for internal walls, the magnitude and angle of the zone adiabatic admittance, computed for a 24 hours' time period, were equalized to yield another 2R1C network i.e., the internal walls were modeled with adiabatic boundary conditions. 1R network was used to model ventilation heat losses and a capacitance was used to represent the mass of the air included in the zone, that

Table 4
Summary of all the BES models developed and reported in the literature.

Work source	Subsystem modeled	Model type	Parameters used for modeling	Experimental realization	Occupancy	Optimization	Objective function	Simulation period	Simulation platform	Validation
Hittle and Bishop (1983)	1-D multilayered slabs (applicable to walls, roof, floor)	Thermal response factor method	Thermo-physical properties of slab	No	No	No	NA	–	BLAST	Analytical proof
Butler (1984)	Multi-layer slabs	Thermal response factor method	Thermo-physical properties of slab, heat flux values of previous time steps	No	No	No	NA	1 h, ¼ h	THERM	Analytical proof (Compared with z-transform method of Stephenson & Mithalas (1971))
Ouyang and Haghighat	Multi-layer slabs	State space method	Thermo-physical properties of slab	No	No	No	NA	1 h	Analytical calculations	Analytical proof (Compared with the method of Stephenson & Mithalas (1971))
Davies (1995)	Building civil structures	State space method	Thermo-physical properties of slab	No	No	No	NA	–	Analytical calculations	
Menezo (2000)	Building envelope (conduction models)	State space		No	No	No	–	–	–	
Wang and Chen [85]	High and low thermal capacity walls	Frequency response models	Thermo-physical properties of the wall, inside and outside surface thermal resistances	No	No	No	–	–	–	Comparison with CTF model
Fraisse et al. (2002)	Multi-layer wall, Hydraulic heating floor, Building space	Frequency response	Thermo-physical properties of the wall, inside and outside surface thermal resistances, water loop temperature	Yes	No	No	–	3 h	TRNSYS (TYPE 100)	Comparison with works of Lafabrie (2001)
Kosny and Kossecka (2002)	Wood, concrete, steel framed walls with high thermal mass and three-dimensional thermal bridges,		Thermo-physical properties of the construction elements, Thermal resistance, roof insulation	No	No	No	–	1 h, 2 h	DOE-2.1E	Experimental
Wang and Chen (2003)	High mass, medium mass and low mass walls	Frequency response models	Thermo-physical properties of the wall, inside and outside surface thermal resistances, sol–air temperature	No	No	No	–	–	–	Comparison with ASHRAE (1997) method
Park et al. (2004)	Double – skin façade system, air flow window system	State space model	Solar radiation, thermo-physical properties, wind air velocity	Yes	Occupant Comfort through PMV method	Non linear constrained optimization, dynamic optimization	Parameter estimation of model and cost function for occupant responsive optimal control	3 h	MATLAB, LABVIEW 6.1	Experimental validation
Wang and Xu (2006, 2007)	High and low thermal capacity walls		Sol air temperature, thermo-physical properties of wall, outside air temperature, horizontal global solar radiation	No	No	Genetic algorithm	Parameter estimation of building space and construction element models	170 h	Not mentioned	Experimental tests
Yan et al. (2008)	Wall, building space, Indoor air quality, HVAC plant	State space method	Indoor temperature, humidity, VOC concentrations (volatile organic compounds), HVAC load	No	No	No	None	95 h	CFD	Compared with simulation of a hypothetical building model

Table 4 (*continued*)

Work source	Subsystem modeled	Model type	Parameters used for modeling	Experimental realization	Occupancy	Optimization	Objective function	Simulation period	Simulation platform	Validation
Xu et al. (2008)	Brick/Cavity wall	Improved frequency domain regression method	Thermo-physical properties of the wall, inside and outside surface thermal resistances	No	No	No	–	–	–	Comparison with TRF and CTF methods of Stephenson and Mithalas (1971)
Li et al. (2009)	ASHRAE wall 24		Thermo-physical properties of the wall, inside and outside surface thermal resistances, number of layers	No	No	No	–	–	–	Comparison with DRF, TRF and CTF methods
Wang et al. (2009)	Building construction elements	Frequency domain regression method for transient time calculations	Thermo-physical properties of the wall, inside and outside surface thermal resistances, CTFs	No	No	No	No	–	–	Comparison with conventional method of heat flow calculation of ASHRAE (1997)
Martin et al.	Multi-layer wall		Thermal inertia of building space, Air temperatures in and outside the control volume under test	Yes	No	No	NA	–	FLUENT 6.2	Experimental
Tindale (1993)	Building fabric elements, air mass, heating and cooling plant	Lumped capacitance	Outside dry bulb air temperature, radiant temperature, solar heat gain incident on wall surface, plant load, thermal mass temperature	No	No	No	–	–	APACHE	Comparison with works of Davies (1991) and analytical validation
Hudson and Underwood (1999)	Building room space without windows	Lumped C	Plant load, Internal causal heat gain, external air temperature	No	No	No	–	220 h	MATLAB/ Simulink	Experimental data
Gouda et al. (2000)	Building space (two external walls, an internal floor, internal ceiling and two partitions), heating system		Incident solar irradiance, wall area, causal heat gains to space, plant heat output, room air temperature, external air temperature, overall thermal resistance							On-field measurements
Skrjanc et al. (2001)	Building room space with window, HVAC plant,	White box, lumped capacitance model.	Weather data (outdoor air temperature, global solar radiation, level of cloudiness), thermo-physical properties of construction elements and windows	Yes	No	Fuzzy logic		1 day	MATLAB	Experimental validation
Gouda et al. (2002)	Building space (two external walls, an internal floor, internal ceiling and two partitions)		Outdoor temperature and solar radiation	No	No	Non linear constrained optimization	Parameter estimation of 3R2C model	465 h	MATLAB	Analytical
Mendes (2003)	Building room space, HVAC plant		Weather data, ground temperature, perturbations, building room temperature	No	No	Fuzzy logic for thermal comfort, On–Off control, PID, robust and adaptive, predictive control of room temperature by HVAC systems		50 h	MATLAB/ Simulink	

Khoury et al. (2005)	Building space, wall, window	White box	Room construction data, thermal conductance of construction elements, solar transmittance and absorptance,	No	No	None	–	160 h	MATLAB/ Simulink	Comparisons with TRNSYS (Type 56) and SIMBAD
Kampf and Robinson (2007)	Building space (two external walls, an internal floor, internal ceiling and two partitions)	Lumped capacitance	Conductance of construction elements, inside and outside air temperature, energy flux from sun to external wall surface, LW radiation from the sun	No	No	No	–	4100 h	C++	Compared with MATLAB model
Bertagnolio et al. (2008)	Building space, HVAC system	Lumped capacitance	Wall properties, outdoor air temperature, humidity levels of room air, heating, cooling and electricity demand	No	No	No	–	700 h	TRNSYS (Type 56)	BESTEST comparison tests
McKinley and Alleyne (2008)	Building space (a room)	Lumped capacitance	Thermo physical properties, solar loads on outer surface of walls	No	No	Unconstrained Hill Climbing algorithm	Root mean squared error for temperature and humidity	22 h	Energy plus, MATLAB 7.1	Validated against model generated data
Sodja and Zupancic (2009a, b)	Walls, windows, room interior, Solar radiation		Wall layer and windows thermal properties, global solar radiation, outdoor temperature	No	No	No	–	120 h	Dymola-Modelica	None
Balan et al. (2009)	Building room	Lumped capacitance	Outdoor air temperature, ground temperature, radiator output	No	No	PID control, predictive control		1400 h	MATLAB/ Simulink	None
Park et al. (2011)	Single zone building room	Lumped capacitance model	Indoor air and surface temperature, outdoor surface and ambient temperature	Yes	No	Unconstrained optimization	Sum squared error minimization	9 days	MATLAB/ Simulink	Experimental
Goyal et al. (2011)	Conduction heat flow through walls, Convection flow through zonal air mass	Black box	Zonal temperature, zonal humidity ratio, supply air flow rate,	No	No	Unconstrained optimization	Minimization of prediction cost function	50 h	MATLAB	On site measurement validation
Ma et al. (2010)	Building space, chillers and cooling tower, thermal storage tank, energy price	Lumped capacitance model	Heat flow from one zone to another, inside and outside air temperature, hourly solar radiation, exit water temperature, mass flow rate of water in chiller	Yes	No	Model based predictive control		4 days		Comparison with historical data
Balan et al. (2011)	Building space (a house)	Black box	Inside and outside air temperature, mean wall temperature, heat input to the air node	Yes	Yes	Model based predictive control	–	24 h	–	None
Vasak et al. (2011)	Wall and windows	Black box	Inside and outside air temperature, heat flux due to solar radiation, thermal resistance and capacitance of walls	No	No	Model based predictive control	Minimization of responses of reference and developed models	720 h	MATLAB	Comparison with model developed in TRNSYS
Nowak and Urbaniak (2005, 2007, 2008, 2010, 2011)	Room (wall, window, roof, floor), heater and ac plant		Room geometry, room zone, radiation data, Predicted Mean Vote index	No	Yes	Generalized predictive control, dynamic matrix control, multi-objective optimization, fuzzy logic	Minimzation of cost function, min–max of energy and comfort	3 h	MATLAB/ Simulink	None

Table 4 (*continued*)

Work source	Subsystem modeled	Model type	Parameters used for modeling	Experimental realization	Occupancy	Optimization	Objective function	Simulation period	Simulation platform	Validation
Ma et al. (2011)	Building thermal zone, HVAC system (AHU and a fan with VAV boxes)		Heat flow from one zone to another, zonal air temperature, air flow rate in and out of the AHU unit, outside air temperature		No	Parameter identification through non-linear regression algorithm, plant control through distributed predictive control	Weighted sum of temperature variation from set point, comfort constraint violation and control efforts for each VAV box and AHU systems	24 h	MATLAB	Logical interpretation
Ferreira et al. (2012)	HVAC (Variable refrigerant flow) system, thermal comfort		Room air temperature, air humidity, global solar radiation, state of doors and window, PMV index	Yes	yes	Neural network based predictive control, multi-objective genetic algorithm	Not mentioned	7 h	Not mentioned	Cross validation* (validated by constructing another data set for PMV calculations)
Privara et al. (2012)	Building room	–	Zone temperatures, ceiling core and core temperatures of common wall, supply water temperatures, solar radiation	No	No	Model predictive control	–	4 h	MATLAB	TRNSYS comparison
Yang and Wang (2012)	Thermal comfort, visual comfort, indoor air quality		Illumination level, carbon dioxide concentration, room temperature	No	Yes	Multi-objective particle swap optimization	Minimize energy and maximize comfort	Not mentioned	MATLAB	None
Wang et al. (2010)	Electric utility situation, occupants comfort		Market information, Illumination level, carbon dioxide concentration, room temperature	No	Yes	Fuzzy logic+PD controller	Maximize comfort and minimize energy	40 h	MATLAB /Simulink	None
Gudi et al. (2012)	Building room, HVAC system, lighting system, motor system		Indoor temperature, luminosity in room, HVAC heat flow, illumination from outside, external zone temperature	Yes	Yes	Model predictive controller	–	60 min	MATLAB /Simulink	None
Brown et al. [86]	Building space, simple HVAC system	White box	Infiltration gain, window and other physical construction elements' conduction loss, HVAC load factor	Case study only	Yes	No	NA	Monthly (1 year)	EnergyPlus	Case study
Asere and Blumberga [87]	Insulation submodel, the total benefits sub-model, construction companies' capacity and financing sub-model and policy instruments	Bottom-up approach	Insulation rate (EUR/m^2), unheated area of the building space under study, time for decision making, economic benefit indexes in EUR p.a.	No	No	No	NA	5 year study till 2020	Not given	Verification tests, sensibility test, parameter verification test, extreme policy and extreme condition tests.
Elarga et al. [88]	Façade with and without blinds		Solar gains and internal loads	No	–	No	NA	1 year	TRNSYS, WINDOW 6	Comparison with DIGITHON model
Ahn et al. [89]	Lighting system	White box	Light power density (W/m^2)	No	No	No	NA	Not mentioned	EnergyPlus	No
Jusoh et al. [90]	Building space subjected to internal loads	CFD	Room air pressure, mean radiant temperature, velocity, PMV and PPD index	Yes	Yes	No	NA	1 h	CFD	Experimental testing
				No	No	Yes				Case study

Gruber and Prodanovic[91]	Customer demand, local generation, storage devices and grid connection	Energy management system	Battery charging or discharging, controllable and non-controllable load, dispatchable generation				Minimizing costs of energy supply to the building energy systems	1 h with a sampling time of five minutes	MATLAB 2012a	
Ashouri et. al. [92]	Building space, resource energy converter, PV system, solar thermal collector, vapor compression system, gas boiler, air source heat pump, battery storage	White box	Discomfort, building temperature, internal loads, electric power (kW) of building under study, grid-demand (kW)	No	Yes	Mixed-integer linear programming	Minimize cost function of investment, operating, and discomfort objective	1 year	MATLAB and Yalmip [93] toolbox	Case study
Yan et al. (2015)	Building space, HVAC system, energy usage	White box	Air temperature, Relative Humidity, Global radiation (kW h/m^2), energy consumption of the building under study	No	Yes	No	NA	Energy consumption monthly for 1 year	Not mentioned	Case study of two different types of buildings with different operation modes and different climates.
Lü et al. (2015)	Building space without windows	Neural network model	Supply air flow rate (m^3/s), internal heat gains, solar heat gain	No	No	No	NA	15 Days hourly samples	HMTB program [94]	Error indication between developed model and already published work
Mullen et al. (2015)	Building space	CFD model	Space temperature,	Yes	No	No	NA	10 h	Phoenics CFD software [8]	Experimental validation
Quan et al. (2015)	Data integration model, urban building energy model, urban roof solar energy model and energy balance model	Grey box	Weather parameters, occupancy load, occupant density,	Yes	Yes	No	NA	1 day	ArcGIS 10.2	Case study: building energy simulation in Manhattan
Yan et al. [95]	Occupancy	White box	Occupancy state, number of occupants, type of activity	No	Yes	No	NA	Not mentioned	Not mentioned	Case studies and experimental validation

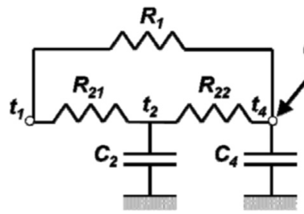

Fig. 5. Laret's RC model [100].

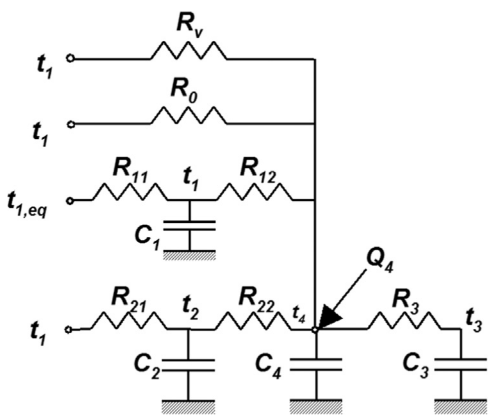

Fig. 6. Ngendakumana's extension of the Laret RC model [101].

mass being multiplied by a factor ranging from 5 to 6 to take into account the lack of homogeneity of the indoor temperature in the zone.

Bertagnolio et al. [102] coupled Masy's model [75] to a complete HVAC system model. A test cell composing of tight insulated steel sandwich boards with the window removed and the environment controlled (to note outdoor temperature) was used to carry out experimental validations of the model. The model was validated against benchmark test cases generated with reference codes (BLAST, DOE-2, ESP, SRES/SUNCODE, SERIRES, S3PAS, TASE and TRNSYS). Such validations resulted in discrepancies especially for the heavy-weight cases due to limited order of the wall model and also due to imperfect control for the heating/cooling system.

To accurately estimate the interactions between indoor ambient and heavy outdoor insulated walls, a more detailed wall model using more than one thermal mass is required. Masy [75] and Bertagnolio et al. [102] developed a residential-building simulation tool to perform comfort analysis and energy consumptions prediction for different heating (or cooling) systems and for various control strategies with the help of an Engineering Equation Solver [103]. The HVAC system model was developed with all the equipments (AHUs, TUs, pumps, fans, and networks) gathered as global components of each type. The connected global HVAC system model included one global Air Handling Unit model, one global Terminal Unit model and one Heating/Cooling Plant model. Air and water networks were also modeled to take pressure drops and heat exchanges into account. Hourly values of indoor temperature, humidity, heating, cooling and electricity demands were computed by the model.

The simulation tool provide performance indicators related to air quality (CO_2 concentration) and thermal comfort (Predicted Percentages of Dissatisfied) as well as gas, fuel and electricity consumptions, primary energy consumption, CO_2 emissions and global energy cost, with accounting for high and low electricity rate hours. An auditing benchmarking tool for commercial buildings was developed by Bertagnolio et al. [102] in order to facilitate an auditor with theoretical reference performances (or benchmarks) in order to carry out analysis and interpret the current performances of the building ("good", "average" or "bad") with accuracy.

Gouda et al. [65] developed a dynamic model using Simulink to simulate thermal behavior of a building and its heating system. Gouda et al. argued that with careful window and shading element design, the solar gain can assist winter heating while giving minimum nuisance overheating in summer-the objective of passive solar design of building spaces. Gouda defined various energy transfer paths in a building space with two external walls as shown in Fig. 8.

State space equations of the form X(dot)=AX+BU; Y=CX+DU were developed with X as the state vector consisting of nodal temperatures and U as the input vector consisting of the outdoor temperature, heat gains from the plant, solar heat gain and casual heat gains. Such a model was realized in simulink (for the first time) as shown in Fig. 9.

Diffuse and direct solar radiation values from the total horizontal (global) radiation value were estimated by using the model developed by Skartveit and Olseth [104]. These values were then used to determine the radiation incident on a building surface as estimated by Lui and Jordan [74]. the zenith angle of the sun together with the diffuse and direct fraction results obtained by Skartveit and Olseth [104] model was calculated using a time-series of incident radiation values on the horizontal, with the time and date of measurement. These values were then inserted into Lui and Jordan [74] model to estimate the equivalent incident solar radiation on a surface at any tilt, surface azimuth angle, latitude and longitude. The model developed by Gouda et al. [65] was investigated for short time scale simulation of relevance to control system synthesis and design.

Now, the massive elements of buildings in common use (e.g., concrete or brick walls) are rarely in steady state and thus it is necessary to conduct transient thermodynamic analysis for heat flow in building constructions. Wang and Chen [73] calculated the response factors (RF) and conduction transfer functions (CTFs) of building constructions using a frequency domain regression (FDR). The method involved calculating the frequency characteristics of the total transmission matrix within the frequency range concerned. An objective function consisting of frequency dependent weighed errors was introduced to solve a set of linear equations and a simple polynomial s-transfer function for internal, cross or external heat conduction, respectively was developed. The problem was linear in nature. A step wise procedure to calculate the RFs and CTFs by applying inverse Laplace transforms or Z-transforms on the polynomial s-transfer function was presented. Computation tests and comparisons for various cases were presented to make the FDR method adequately accurate for the practical applications of engineering and building simulation.

Park et al. [80] developed a 1R1C lumped parameter network to model heat gain due to home appliances in a well-insulated room. The test room was equipped with a temperature acquisition device and a number of thermocouples, two in the outer side of the room to measure outside air and wall temperature and sixteen inside the room to estimate the indoor temperature. Incandescent lamps were used as heat sources to identify the global thermal parameters; thermal resistance and thermal capacitance, of the model. From the heat balance equation, indoor temperature in both cases of power source on and off was obtained. And by transient analysis of the thermal network, the value of global thermal resistance was computed. Value of global thermal capacitance was calculated by computing the time constant of the network using least squares method. Simple differential equations were used to represent the nodal temperatures of the model and using these equations the model was developed in MATLAB/Simulink. The indoor temperature including the room air temperature, the furniture temperature and the wall temperature were considered homogeneous.

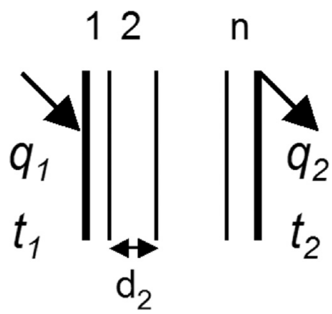

Fig. 7. Multi-layer wall with sinusoidal response of heat flow [75].

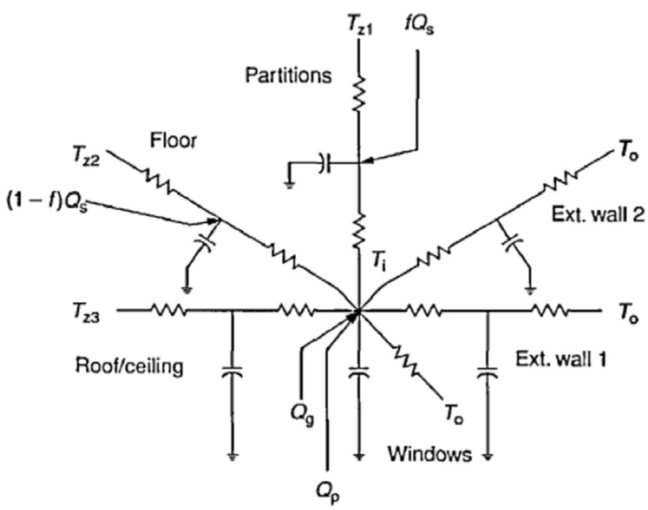

Fig. 8. Gouda's model of a perimeter room [65].

The thermal resistor and the thermal capacitor of the room were not distinguished by each thermal coefficient of materials and there was no additional heat flux from solar radiation, metabolism, infiltration, ventilation and air leakages by window, door, thermal bridges or any small hole.

Vasak et al. [105] used a 3R2C network to model a single-story house with two rooms and an attic. A state space model including a disturbance vector was developed in MATLAB. The disturbance vector included the outside temperature and heat flux from solar radiation, and input vector was the heat flux necessary to keep the temperature inside of the room at a given reference i.e., input vector was the heat flux from the actuator (radiator, HVAC, etc.). An identical model developed in TRNSYS was used as the reference model and both models were excited with the same input of outside temperature and heat flux from solar radiation for all surfaces in a one month time. A small difference between both the models was noticed on comparing the output of both models. No heating/cooling was performed when the outside temperature was within the given temperature limits and thus, the model allowed to optimally manage heating and cooling in accordance with the current and predicted weather conditions.

Based on the state space principle of modern control theory, Ouyang and Haghighat [68] developed a methodology for calculating thermal response factors of building envelopes. Rational fractions of an s-transfer function were obtained from a simple series expansion and then the state space equation of the system was established and the state transition matrix was calculated. Finally, the response factors were obtained by a series of matrices multiplications after discretizing the continuous system. Linear interpolation between two adjacent instants was used to develop a state equation for the linear time-invariant discrete systems with single input and single output. The state of the system at any $(n+1)$th instant was not only related to the state of the system and input value at the previous time, but also to the input value at the present instant, n. Given the time series of the input (a triangular impulse) and of the output functions, thermal response factors were computed using state equation. After calculating the state transition matrix, the response factors were calculated by a series of matrix multiplications. An example was presented to illustrate the use of this approach methodology for calculating the thermal response factors of a 5-layer wall. Such a method was simple (though less accurate) and avoided the need to calculate the roots of the system transfer function and there were no miscalculations due to missing of roots.

Nowak and Urbaniak [106] modeled a room of a building in MATLAB/Simulink. The mathematical simulation model included physical parameters of construction elements like that of walls, floor and roof considering information on the room geometry, thermal properties of the room materials, thermal resistance of the room, heater characteristics (temperature of hot air, flow rate), air-conditioning characteristics and initial room temperature. Control of energy consumption in a building is connected with the heating and cooling equipments. The main goal of achieving energy efficiency in buildings is to develop control strategies for reducing electrical energy consumption, keeping in view of the indoor air conditions related to thermal comfort of the occupants. Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) and Draught Rating (DR) are three indexes that can be used to control thermal comfort in a room.

A hierarchical structure was developed by Nowak and Urbaniak in their works of [106–110,76,77] which comprised of four layers of the hierarchy, formulating a set of partial goals viz., direct control layer (responsible for security controlled process; classic PID and fuzzy logic), supervisory control layer (responsible for calculating fixed points for direct control layer; Predictive Control), optimization layer (responsible for realization of the three indexes to estimate thermal comfort) and planning layer (optimizing climate comfort maximization against energy consumption minimization).

In [106], predictive control algorithms were formulated defined by the process model related to control purposes, where the occupants thermal comfort sensation was given by PMV calculations. PMV values were calculated by using a nonlinear mathematical model of thermal comfort which was included in the cost function. Two predictive control algorithms viz., dynamic matrix control and generalized predictive control algorithms were formulated to optimize the PMV index values.

Li et al. [83] developed a heat flux comparison test method to verify the accuracy of the CTFs solved through direct root finding (DRF) method, state space (SS) method and the frequency domain regression (FDR) method. Calculation principles of the three methods were implemented on ASHRAE wall 19 and 24 [5]. The developed method verified the accuracy of CTFs by checking difference between heat flux calculated by CTF method and by analytical solution. In the test, ASHRAE Loads Toolkit (2001) algorithm [5] was used to calculate SS and DRF CTF solutions. The inside and outside film coefficients of the test wall were treated as resistive layers. Inside temperature was regarded as constant. Outside temperature was taken to be of a 24 h steady periodic profile approximated for 1-h time steps as shown below.

$$T_O = T_m + T_A \sin\left(\frac{\pi}{12}\tau\right) \tag{5}$$

where T_0 is the outside air temperature, T_m is the mean air (inside) temperature, and T_A is the amplitude temperature.

Khoury et al. [111] developed a generic multizone building model using Matlab/Simulink environment and implemented into the SIMBAD Building and HVAC Toolbox. Air zone model was developed

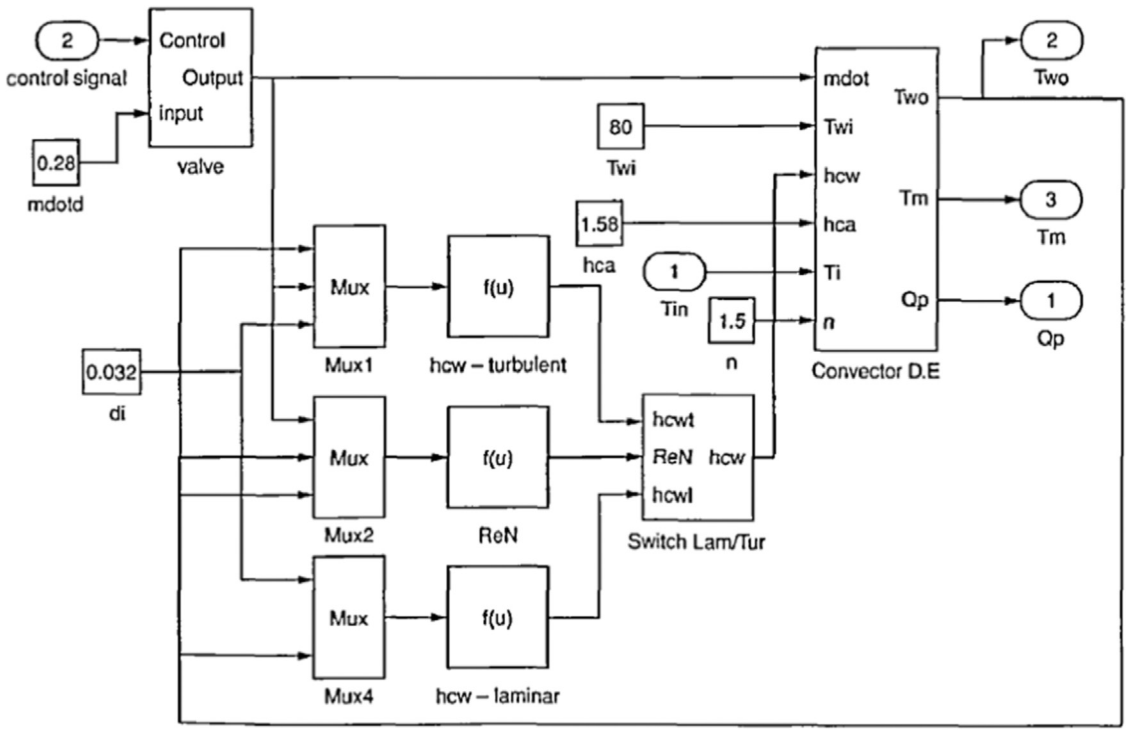

Fig. 9. Model realization in MATLAB/Simulink [65].

using mathematical formulations of the zone heat balance equations. Such a zone model involved homogeneous treatment of each zone and every zone had two set points: one for cooling and one for heating. The zone air temperatures vary between these two set points. To be used into the multizone model, the equations were defined in matrix form, for all zones of the building. Basic heat conduction equation was used to model multilayer walls which involved knowledge of thermophysical properties for each layer of the wall. The heat transfer was assumed to be one-dimensional. The wall surfaces were assumed to be of two kinds: those in contact with air and those with imposed surface temperature (boundary surfaces). A set of partial differential equations representing the boundary conditions were discretisized using a combined finite difference and finite volume technique. The window model involved a relatively simplified model for external windows with sun blinds. The window solar transmittance and absorbtivity were assumed independent from the incidence angle of the solar radiation and thus the same solar transmittance and absorbtivity were made use for both beam and diffuse component of the solar radiation. Clear part and shaded part of the windows were modelled by two temperature nodes: interior node and exterior node, neglecting the window thermal inertia.

Ferreira et al. [112] developed a model based predictive control methodology, which is: assessed using the Predictive mean vote (PMV) index (computed by means of a heat-balance equation), implemented by radial basis function neural networks, identified by means of a multi-objective genetic algorithm and applied to control HVAC systems in buildings to maintain a desired level of thermal comfort and to minimize the energy spent in doing so. A discrete branch and bound approach was used to optimize the cost function. The model was tested on rooms equipped with sensors to monitor the air temperature, air humidity (SHT11 sensors from Sensirion), global temperature (measured by a black globe thermometer), the state of windows (open/closed), and movement using a passive infra-red activity monitor installed at one corner of the room. The HVAC system was monitored and centrally controlled by a PC management station to which all the external and internal units were connected via a LonWorks communication bus. Two sets, one for winters and one for summers, of predictive air temperature and humidity models were designed. The developed system showed appreciable energy savings during winter season only but the model did not had an input accounting for the room usage, consequently the control algorithm was not able to foresee and act preemptively to counteract the strong impact caused by a flock of people entering the room.

Karmacharya et al. [113] developed a lumped node building element model, in which the construction elements were broke-up into different number of elements having uniform temperature; a solar radiation model, which is a combination of two sub models – first sub estimates the diffuse and direct solar radiation from the global horizontal solar radiation and the second sub uses these values to determine the solar radiation incident on the building surface; and a heating system model – a third order model used to represent a heat exchanger and its water connection. Active occupancy pattern was developed for weekdays and weekends and results obtained from the developed model in matlab showed little variations against the actual data, as the model did not consider heating from the building floor and ground.

Marchiori et al. [114] developed a building energy management control system using wireless sensor networks where sensors and controllers are allowed to efficiently share information, using protocol independent multicast, in a distributed peer-to-peer fashion. An energy controller, containing a power meter to measure real-time power usage and total energy usage independently for each outlet to which it is connected and a Tyco relay, was designed which consumes data coming from a motion sensor, a door sensor and an ambient light sensor. The controller, configured with two outlets one switched and one non-switched, detects and processes the available sensor data and intelligently controls the switched outlet to save energy by switching off nonessential devices when the office is unoccupied, on the basis of a control algorithm programmed into it. Developed algorithm can only work when the room is unoccupied.

Dong et al. [115] developed a method which integrates local weather forecasting (temperature, solar radiation and wind speed) with occupant behaviour detection (number of occupants and occupancy duration), for integrated building heating, cooling and ventilation control to reduce energy consumption and maintain indoor temperature set points. A virtual model of the building is developed in MATLAB/Simulink, to which the weather and occupancy information are fed into. 2C3R model of ASHRAE was used to model heat transfer through external walls, Hammerstein Wiener model and adaptive Gaussian process method was used to model and predict outside dry bulb temperature, global horizontal solar radiation and wind speed and hidden Markov Model for occupancy detection. A non-linear model predictive control was constructed and solved by dynamic programming. The model developed was of appreciable accuracy and showed significant energy reductions.

Lu and Viljanen [116] developed a mathematical procedure to solve a one dimensional heat transfer equations analytically and validated against numerical solution. A single zone building with the construction elements of similar thermo-physical properties were modeled. Outdoor temperature, accounted by the combined effect of the outdoor dry bulb temperature and the solar radiation, was modeled as time dependent Fourier series. The solution technique produced closed form solutions for transients occurring for both indoor and construction element temperatures. However, several non-practical assumptions were adopted which made the technique unsuitable to be applied under real case scenarios. However, it formed as a good first time exercise for solving a one dimensional partial differential heat conduction problem.

4.1. Parameters used in building energy modeling

The parameters and thus variables defining them affecting cooling load calculations are numerous; often difficult to define precisely, and always intricately interrelated. Many energy consuming components vary widely in magnitude, and possibly direction, during a 24 h period. Because these cyclic changes in load components often are not in phase with each other, each component must be analyzed to establish the maximum energy load for a building or zone. A zoned system (i.e., one serving several independent areas, each with its own temperature control) needs to provide no greater total cooling load capacity than the largest hourly sum of simultaneous zone loads throughout a design day; however, it must handle the peak cooling load for each zone at its individual peak hour.

At some times of day during heating or intermediate seasons, some zones may require heating while others require cooling. The zones' ventilation, humidification, or dehumidification needs must also be considered. Table 5 presents a compact list of all the significant parameters used while developing an effective BES model.

4.2. Socio – economic aspects of building energy modeling

With a view to establish an energy – economy relationship in the energy sector, most of the energy planning and management efforts were directed towards development of building energy models. The primary target of such energy models was to estimate building energy demands in the future [140]. Thus, a single criteria approach aimed at identifying the most efficient supply options at a low cost was popular during 1970s [141]. A decade later, with growing environmental concerns, the need to incorporate environmental and social considerations in building energy planning and management resulted in the increasing use of multi-criteria approaches [142].

Multi-objective linear programming has been a usual planning methodology for considering the environmental and economic parameters for building energy planning and modeling and also assisting in the selection of a compromise solution [143]. Multi-criteria decision making (MCDM) techniques have been used for energy planning and management since last decade [144]. MCDM techniques have been popular in Integrated Renewable Energy Systems (IRES) planning, Hybrid Energy Systems (HES), building energy management systems, electric utility planning and other related areas of energy planning and management [145]. Building energy management refers to design, selection, installation and building energy management options in a multi-criteria environment. With the advent of sophisticated computational techniques and tools available, energy modeling and planning for buildings along with appreciable considerations to the society, infrastructure available and economy is possible.

To cater to the needs of the society, vernacular buildings have come into existence. Such buildings tend to emerge the environmental, cultural, technological, economic, and historical aspects of its existence over a period of time. In order to facilitate design and energy modeling of such buildings, building energy codes such as ECBC [146] should include benchmarking measures of 'passive design potential' as a wholly closed air-conditioned buildings can have adverse impacts under erroneous modeling conditions [147]. Therefore, it is necessary to develop practical benchmarks for energy modeling of passive and low energy buildings keeping in view of the socio-economic and techno-economic barriers [148].

Table 5
List of the significant parameters used in development of BES models.

S. No.	Name	Description	Nature	Application[a]
1	Solar radiation	Incident solar radiation is the major thermal load at the building envelope's exterior	Uncontrollable	R/NR
2	Sol–air temperature/outside air temperature	Sol–air temperature is the outdoor air temperature that, in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with outdoor air [5]	Uncontrollable	NR/R
3	Room air temperature	Indoor temperature variations depend on the purpose and occupation of the building	Controllable	R/NR
4	Thermo-physical properties of construction elements	Thickness	Uncontrollable	R/NR
5	Wind characteristics and precipitation	Wind speed, wind direction, and terrain roughness	Uncontrollable	NR
6	Internal heat gains	Internal heat gains from people, lights, motors, appliances, and equipment can contribute the majority of the cooling load in a modern building	Controllable	NR
7	Sky or cloud conditions	Shading, cloudiness of the outdoor weather conditions	Uncontrollable	NR/R
8	Ventilation rate	Flow rate due to intentional introduction of air from the outdoors into a building	Controllable	NR
9	Building location (Global Information)	Information about latitude, longitude, time zone, month, day of month, directional orientation of the zone, and zone height (floor to floor)	Uncontrollable	NR/R

[a] R: Residential buildings; NR: Non-residential (commercial and industrial) building.

Table 6
List of building energy simulation programs.

S. No.	BESP	Applications	Open source	Simulation engine	Limitations
[117]	Autodesk Green Building Studio	3D CAD/BIM	Y	DOE-2.2 and EnergyPlus	Limited for architectural designing; lead to complex modeling and thus, not suited for control purposes
[118]	BSim	Energy, daylight, thermal and moisture analysis, indoor climate	N	Self	No standardized result reports. No possibility batch processing of simulation models at this time – typical simulation time for an average model is though only a few minutes on an up to date computer. No support of geometrical input from CAD tools in IFC file formats –this facility is presently being developed
[119]	Building Energy Analyzer	Heating, on-site power generation, heat recovery, CHP	N	DOE-2.1E	General knowledge of commercial building HVAC systems, and on-site power generation technology is needed to fully utilize Building Energy Analyzer potential
[120]	BuildingSim	Thermostat, simulation, energy cost	Y	Self	Simulation step size is small, so simulation time takes longer than some competitors
[121]	COMSOL Multiphysics	Solving 3-D heat PDE	N	Self	For solving coupled systems of ordinary differential equations (ODEs)
[122]	DesignBuilder	Building energy simulation, visualisation, CO_2 emissions, solar shading, natural ventilation, daylighting, comfort studies, CFD, HVAC simulation, pre-design, early-stage design, building energy code compliance checking, OpenGL EnergyPlus interface, building stock modelling, hourly weather data, heating and cooling equipment sizing	Y	Self	A range of common HVAC systems is available from within the DesignBuilder user interface but users requiring a wider range of different HVAC types should consider exporting EnergyPlus IDF input files and working in the EnergyPlus IDF editor. An advanced HVAC interface to a wide range of EnergyPlus HVAC systems will be available early 2007
[123]	Designer's Simulation Toolkit (DEST)	Building simulation, design process, calculation, building thermal properties, natural temperature, graphical interfaces, state space method, maximum load	Y	Self	The speed of exporting reports is a little slow
[124]	DOE-2	Energy performance, design, retrofit	N	Self	High level of user knowledge
[125]	ECOTECT	Environmental design, environmental analysis, conceptual design, validation; solar control, overshadowing, thermal design and analysis, heating and cooling loads, prevailing winds, natural and artificial lighting, life cycle assessment, life cycle costing, scheduling, geometric and statistical acoustic analysis	N	Energy Plus	As the program can perform many different types of analysis, the user needs to be aware of the different modelling and data requirements before diving in and modelling/importing geometry. For example; for thermal analysis, weather data and modelling geometry in an appropriate manner is important; and appropriate/comprehensive material data is required for almost all other types of analysis. The ECOTECT Help File attempts to guide/educate users about this and when/how it is important
[126]	EnerCAD	Building Energy Efficiency; Early Design Optimization; Architecture Oriented; Life Cycle Analysis	N (Free lower end versions for educational institutions)	Self	Simplified calculation algorithm (monthly heat balance method)
[127]	Energy Expert	Energy tracking, energy alerts, wireless monitoring	N	Self	Energy Expert is used for optimizing the energy performance of existing buildings. It is not used for building design or energy simulation.
[128]	EnergyPlus	Energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance	Y	Self	Text input may make it more difficult to use than graphical interfaces.
[129]	eQUEST	Energy performance, simulation, energy use analysis, conceptual design performance analysis, LEED, Energy and Atmosphere Credit analysis, Title 24, compliance analysis, life cycle costing, DOE 2, PowerDOE, building design wizard, energy efficiency measure wizard	Y	DOE 2.2	Defaults and automated compliance analysis has not yet been extended from California Title 24 to ASHRAE 90.1. It does not yet support SI units (I-P units only). Ground-coupling and infiltration/natural ventilation models are simplified and limited. Daylighting can be applied only to convex spaces (all room surfaces have an unrestricted view of each surface) and cannot be transmitted (borrowed) through interior glazed surfaces. Custom functions in DOE-2.1E (allows users limited customization of source code without having to recompile the code) have not yet been made available in DOE-2.2 or eQUEST
[130]	ESP-r	Energy simulation, environmental performance, commercial buildings, residential buildings, visualisation, complex buildings and systems	N	Self	It is a general purpose tool and the extent of the options and level of detail slows the learning process. Specialist features require knowledge of the particular subject. Although robust and used for consulting by some groups, ESP-r still shows its research roots

[131]	Facility energy decision system (FEDS)	Single buildings, multibuilding facilities, central energy plants, thermal loops, energy simulation, retrofit opportunities, life cycle costing, emissions impacts, alternative financing	Y	None	Not a buildings design tool
[132]	Heat, air and moisture simulation laboratory (HAMLab)	Heat air and moisture, simulation laboratory, hygrothermal model, PDE model, ODE model, building and systems simulation, MatLab, SimuLink, Comsol, optimization	Y	MATLAB – Simulink, COMSOL	Matlab, SimuLink & FemLab needed. Some Matlab expertise needed
[133]	HEAT2	Heat transfer, 2D, dynamic, simulation	No	Delphi	Cartesian coordinates must be used (sloped boundaries are modeled using 'steps')
[134]	ParaSol	Solar protection, solar shading, windows, buildings, solar energy transmittance, solar heat gain coefficient, energy demand, heating, cooling, comfort, daylight	Y	None	Only one strategy for controlling sunshades is available
[135]	PVcad	Photovoltaic, facade, yield, electrical; electrical engineers planning grid-connected photovoltaic systems, especially photovoltaic facades; CAD	Y	Self	Only a German-language version available, Input of building geometry only via DXF import or with ASCII text containing list of 3D-coordinates. Weather database not expandable by the user
[136]	RIUSKA	Energy calculation, heat loss calculation, system comparison, dimensioning, 3D modeling	N	DOE-2.1E	Only the predefined HVAC systems are available
[137]	SIMBAD Building and HVAC Toolbox	Transient simulation, control, integrated control, control performance, graphical simulation environment, modular, system analysis, HVAC	N	MATLAB-Simulink	The toolbox does not currently offer a fully multi-zone building
[138]	SPARK (Simulation Problem Analysis and Research Kernel)	Object-oriented, research, complex systems, energy performance, short time-step dynamics	N	Self	High level of user expertise in system being modeled required
[139]	TRNSYS	Energy simulation, load calculation, building performance, simulation, research, energy performance, renewable energy, emerging technology	N	Self	No assumptions about the building or system are made (although default information is provided) so the user must have detailed information about the building and system and enter this information into the TRNSYS interface

Modeling characteristics	**Building energy simulation programs**								
	BLAST	**BSim**	**DeST**	**DOE-2.1e & 2.2**	**ECOTECT**	**EnergyPlus**	**eQuest**	**ESP-r**	**TRNSYS**
Simulation solution	PI	CI	PI	NI	NI	CI	CI	CI	CI
Time step approach	PI	PI	OI	NI	NI	CI	PI	CI	PI
Geometric description	CI	CI	CI	CI	CI	PI	CI	CI	CI
Simultaneous radiation and convection	CI	CI	CI	CI	NI	CI	CI	CI	CI
Combined envelope heat and mass transfer	CI	CI	NI	NI	NI	CI	NI	CI	CI
Solution method for conduction transfer of heat	TFM	NI	TFM	TFM	FDM	TFM	TFM	FiDM	TFM
Internal mass considerations	CI	CI	CI	CI	CI	CI	CI	CI	CI
Occupant comfort	CI	NI	NI	NI	PI	CI	NI	PI	PI
Solar gains, shading and sky considerations	NI	NI	PI	NI	CI	CI	PI	PI	CI
Variable construction element properties	NI	NI	NI	NI	CI	NI	NI	NI	NI
PCMs	NI	NI	OI	NI	NI	NI	NI	OI	OI
EIA	PI	NI	NI	PI	NI	CI	PI	PI	OI

Nomenclature:
CI: Completely/wholly implemented (Issue is well addressed and backed by program's supportive documentation); PI: Partially implemented (Issue is partially implemented and is not fully addressed by the program); OI: Optionally implemented (Issue is addressed for research and is not included in the standard feature); NI: Not/Negligibly implemented (Issue is not included or only a very small part of it is implemented in the programs); TFM: Transfer Function Method; FDM: Frequency Domain Method; FiDM: Finite Difference Method.

4.2.1. Concept of Passive Architectural Design Index (PADI) for sustainability

In pursuit to sustainable architecture and buildings, a reversible design index is proposed that can effectively define passive/seasonal/hybrid/closed building. Passive Architectural Design Index (PADI) is an approach of benchmarking the building energy efficiency by defining a critical threshold limit beyond which the usage of air conditioning in buildings becomes indispensable to achieve occupant thermal comfort [149].

Developing PADI requires broad data collection and field analysis studying various architectural and urban characteristics such as climate, building typologies, building materials, housing density, land usage, building materials, housing density, etc. The data collection is focused on the state of the matters in building construction and technology and also, on the past, existing, modern and innovative passive building techniques. Computational methods are used to develop calibrated models to validate the data against the empirical data.

5. Building energy simulation programs

Selecting a building energy analysis program depends on its application, number of times it will be used, experience of the user, and hardware available to run it. The first criterion is the ability of the program to deal with the application. For example, if the effect of a shading device is to be analyzed on a building that is also shaded by other buildings part of the time, the ability to analyze detached shading is an absolute requirement, regardless of any other factors.

Table 6 presents a detailed wise summary of all the BESPs which assist in development, evaluation and validation of a particular BES model.

6. Conclusion

Building energy modelling and control has gained significance since, last decade and a large number of research facilities have been working on developing control strategies with a view to reduce net energy usage within a building and thus, striving towards sustainability. Effectiveness of a particular control strategy majorly depends on how well the building model has been developed and calibrated. In almost all control projects, it is crucial to have good precise models of the systems in order to design and tune the controllers and to simulate their performance.

Now, building energy modelling and control is an interdisciplinary area of study which involves concepts and studies of electrical and electronics engineering, mechanical engineering, civil engineering and also, architecture. A compact and effective review article describing underlying principles of energy transfer processes occurring within a building was necessary. An attempt has been made to achieve such an objective. Concept of BES with approach adopted to develop BES model has been presented. Significant parameters taken into consideration in development of a BES model has been described. Based on the review study a few knowledge gaps have been recognised.

Building energy modelling research has mainly dealt with network topology (structure of the network), but more research is needed on the influence of input parameters like that of solar irradiation, occupancy, etc. A systematically developed simplified building model, dealing with temperature, heat and relative humidity is lacking. Techniques used in modelling lack computational efficiency and majority of the developed models are predicted models. Dynamic response of models developed by researchers still lacks accuracy. Models which are accurate to a fair degree require a large computer memory and processing or computation time.

A comprehensive building energy model fully integrated into advanced control for accuracy and robustness has not been reported. Though models have been developed for occupancy pattern behaviour, thermal behaviour of construction elements and of room zone, hvac and lighting systems but an integrated modelling approach to analyze the effects of the factors on net energy consumption has not been reported. Impact of building thermal mass as well as several other measures such as reducing lighting levels, increasing thermostat set points, adjusting supply air temperature, resetting chilled water temperature on net energy consumption pattern of buildings needs more research.

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